Chapter 3
Storm Runoff Solids Loading

Introduction
This chapter presents methodologies for using relatively simple equations to estimate pollutant loading from urban drainage areas. The loading equations in this chapter account for floatable solids or street litter, highway sand due to winter deicing, street dust and dirt, and eroded soil-sediment from open space. The calculated results only indicate a magnitude of solids loading. For designing a stormwater pollution control system, field sampling and monitoring data are required to verify the estimated results.

Litter/Floatables
A large amount of the litter that enters urban drainage systems reaches receiving waters. Urban litter consists mainly of manufactured materials, e.g., such as plastic and paper wrapping, shopping bags, cigarettes and their packets, and items used in public parks, gardens, and fast food outlets. The total amount of material discharged can vary significantly depending on the degree to which the watershed is littered. Five studies (conducted in the NY/NJ Metropolitan Area; Jamaica Bay, NYC; Fresh Creek, NYC; Hartford, CT; and Newark, NJ) looked at the total amount of solid material discharged from CSOs on a dry weight basis and reported between 0.02 and 1.7 lb/acre/in. of rainfall (Newman and Leo, 2000).

A study in the City of Auckland, New Zealand (Cornelius et al., 1994) indicated that the annual litter loading rates from commercial, industrial, and residential areas are 1.35, 0.88, and 0.53 kg/ha-yr, dry weight bases (or 0.014, 0.009, and 0.006 m^3/ha-yr), respectively. The litter's bulk densities vary with land use (96.4 kg/m^3 for commercial, 97.8 kg/m^3 for industrial, and 88.3 kg/m^3 for residential areas). Although the commercial and industrial areas produced higher annual loadings per unit area, the residential areas contribute more total litter than all other areas combined because residential development occupied the largest area. Armitage and Rooseboom (2000) developed an empirical equation to determine annual volume of litter for South Africa:

$$T = \Sigma f_{sci} (V_i + B_i) A_i \quad \text{...}(1)$$

Where:
- T = total litter load in the waterways (m^3/yr)
- f_{sci} = street cleaning factor for each land use (varies from 1 for regular street cleaning to about 6 for no street cleaning services)
- V_i = vegetation load for each land use (varies from 0.0 m^3/ha-yr for poorly vegetated areas to about 0.5 m^3/ha-yr for densely vegetated areas)
- B_i = basic litter load for each land use (1.2 m^3/ha-yr for commercial; 0.8 m^3/ha- yr for industrial; and 0.01 m^3/ha-yr for residential)
- A_i = area of each land use (ha)

For each storm (>1 mm of rainfall) the litter volume can be estimated by using the following equation (Armitage and Rooseboom, 2000):

$$S = f_s\, T / \Sigma f_{si} \quad \text{……(2)}$$

Where: S = storm load in the waterways (m^3/storm)

f_s = storm factor (varies from 1.0 for storms occurring less that a week after a previous >1mm storm; to about 1.5 for a storm occurring after a dry period of about three weeks; to about 4.0 for a storm occurring after a dry period of more that about three months)

T = total litter load in the waterways (m^3/yr)

Σf_{si} = the sum of all the storm factors for all of the storms in the year (since this information is generally not available, a suggested alternative is to count the average number of significant storms in a year and multiply by 1.1)

Roadway Sanding for Snow/Ice Events

Roadway sand application is a common practice during the winter snow season for increasing track friction between highway surfaces and automobile wheels. Sanding is important to public safety because it provides safe conditions during treacherous winter weather. However, after snow-melt, sand becomes part of highway nonpoint source pollutants. Guo (1999) developed a method to determine the sand recovery during winter highway sanding. The sand recovery rate is defined by the ratio of the annual sand amount collected by the highway drainage system to the annual sand amount applied to the highway. The method is being adopted for estimating the amount of sand that escapes into the environment.

During winter, the total amount sand application can be estimated as:

$$W_s = w_s B_t L \quad \text{……(3)}$$

Where: W_s = sand amount in kg or lb
w_s = annual unit sand amount in kg/m^2 or lb/ft^2
B_t = width of traffic lanes in m or ft
L = distance of highway between two adjacent culverts in m or ft

A typical highway drainage hydraulic routing system for the snow removal process includes: (1) piling snow on both sides along the highway shoulders for snow storage; (2) roadway drainage gutter; (3) highway runoff collection system for releasing runoff that contains various types of pollutant with different concentrations to receiving streams. During a snow plowing operation, sand is applied only to traffic lanes. Snow mixed with sand are removed from the traffic lanes to a storage area which is located along the highway shoulders for compacting and piling. The captured snow volume can be estimated as

$$V_c = H_m B_s L \quad \text{……(4)}$$

Where: V_c = captured snow volume in m^3 or ft^3
H_m = maximum height of snow pile in m or ft
B_s = width of storage area in m or ft
L = distance of highway between two adjacent culverts in m or ft

Snow removed from the highway is placed in the storage area along highway with a maximum height of 7.5 ft. The compacted snow volume between two adjacent culverts can be estimated as

$$V_s = n\, m\, P_s\, B\, L \quad \text{……(5)}$$

Where: V_s = compacted snow volume in m^3 or ft^3
P_s = equivalent water depth to annual fresh snowfall depth
n = snow compact ratio, defined as 1 ft fresh snowfall equivalent to n ft compacted snow
m = snow-to-water depth ratio, defined as m ft fresh snowfall to produce 1 ft of water
B = total width of the paved highway area including traffic lanes, shoulder areas, and snow storage areas in m or ft
L = distance of highway between two adjacent culverts in m or ft

The snow volume capture rate (r) from the highway/paved surface by the storage area is defined by Guo (1999) as

$$r = V_c / V_s \quad (6)$$

Since snow and sand will be well mixed during the plowing process, the amount of sand captured during this process and stored in the snow storage area is

$$W_c = r\, W_s \quad (7)$$

Where:

W_c = sand amount in weight captured by the snow storage area
W_s = sand amount in weight applied
r = snow capture rate by storage area, which is the ratio of captured snow volume to the compacted snow volume in the storage area.

After snow melt, the recovery amount of the sand remaining in the storage area that needs to be recovered by street sweeping equipment is estimated as follows:

$$W_m = R_m\,(W_c - W_b) \quad (8)$$

Where:

W_m = sand amount in weight collected by machine
W_b = sand amount in weight transport by runoff
R_m = efficiency of sand collection by machine, such as 0.80 to 0.90, depending on field operations

The sand amount transported (W_b) through the highway drainage ditch can be estimated by the event mean concentration method (Urbonas et al., 1996; Mosier, 1996):

$$W_b = \gamma_s\, E_w\, V_o \quad (9)$$

Where: γ_s = specific weight of sand
E_w = empirical value of event mean concentration
V_o = total annual runoff volume

The sand recovery (W_t) between two adjacent culverts is:

$$W_t = W_m + e\, W_b \quad (10)$$

In which: e = 1 for sand collection with a sand basin at the end of drainage system, or e = 0 for direct release through a culvert to the receiving stream. Therefore, one may estimate that the annual sand emitted to the environment would be $W_s - W_t$. In a case study, Guo (1999) reported that about 30% of solids were transported by storm runoff and collected by stormwater storage basins. Thus, without stormwater detention basins, this amount of solids would be discharged to receiving streams.

Street Dust and Dirt Accumulation

Sartor and Boyd (1972) reported that the build-up of dust and dirt between street cleanings was non-linear and of an inverse exponential form over a period of up to 10 days. Huber and Dickinson (1988) used three types of equations in the U.S. EPA's Stormwater Management Model (SWMM) for estimating the loading of dust and dirt accumulation:

Power-Linear Equation: $$DD = DDFACT\,(T^{DDPOW}) \qquad (11)$$
$$DD \leq DDLIM$$

Exponential: $$DD = DDLIM\,(1 - e^{-DDPOW \cdot T}) \qquad (12)$$

Michaelis-Menton: $$DD = (DDLIM)(T)/(DDFACT + T) \qquad (13)$$

Where:

DD = amount of dust and dirt accumulation, g
T = time, d

Units for *DDFACT* (a coefficient), *DDPOW* (an exponent), and *DDLIM* (the build up limit) are shown in Table 5.

Table 5. Dimensional units for dust and dirt accumulation equations coefficient

Equation	*DDFACT*	*DDPOW*	*DDLIM*
Power-Linear Equation	$g \bullet day^{(-DDPOW)}$	Dimensionless	g
Exponential	Not Used	day^{-1}	g
Michaelis-Menton	day	Not Used	g

Delleur (2001) indicates street dust and dirt loading are the result of deposition and removal rates plus permanent storage that is not removed by street cleaning equipment, as summarized in Table 6.

Table 6. Average values and range of street dust and dirt accumulation load

Type of Street	Initial Loading (g/curb-m)	Daily Deposition Rate (g/curb-m/d)	Maximum Observed Loading (g/curb-m)	Days To Observed Maximum Loading
Smooth/Intermediate Textures				
Average	150	9	>270	>25
Range	35 – 710	1 – 40	85 – 910	5 – 70
Rough/Very Rough Textures				
Average	370	15	>750	>30
Range	190 – 630	6 – 34	370 – (>1400)	10 – (>50)

Street Dust and Dirt Washoff

Based on field study by Sartor and Boyd (1972), the washoff can be expressed by the following first-order decay equation:

$$N = N_0\,(1 - e^{-KR}) \qquad (14)$$

Where:

N = amount of street dust and dirt washoff, g/curb-m
N_0 = amount of initial street dust and dirt, g/curb-m
K = washoff coefficient (ranged 0.167 – 1.007 depending on rain intensity, street dirt loading category, and street texture category)
R = total rain depth, mm

Washoff is more efficient for the higher rain energy and smoother pavement (Delleur, 2001).

Soil Erosion

Soil erosion from an open land is considered by many to be a problem to receiving-water quality. The amount of soil loss can be computed by the Revised Universal Soil Loss Equation (RUSLE). The RUSLE computes sheet and rill erosion from rainfall and the associated runoff for a landscape profile. The equation is written as (Renard et al., 1996):

$$A = R \text{ x } K \text{ x } LS \text{ x } C \text{ x } P \quad \text{(15)}$$

Where: A = annual soil loss from sheet and rill erosion, tons/acre
R = rainfall and runoff factor; ranged 80–94
K = soil erodibility factor; depended on soil type and organic matter, for 2–4% of organic matter, ranged 0.4–0.25
LS = slope length and steepness or slope length-gradient factor
C = cover and management factor; legume, C = 0.005; ryegrass, C = 0.1
P = support practice factor; 0.3−1.0

The slope length-gradient factor (LS) can be determined by Equation 16 below:

$$LS = [0.065 + 0.0456\,(slope) + 0.006541\,(slope)^2]\,[(slope\ length)/72.5]^{NN} \quad \text{(16)}$$

Where: *Slope* = slope steepness, %
Slope length = length of slope, ft
NN = slope steepness factor, ranged 0.2–0.5

Individual factor values can be entered directly into the formula or calculated from information provided by the user. The equations given are empirical and can be used for planning purposes. Actual measurement of pollutants is always the best way to understand and predict pollutant loads specific to any watershed, but it is often expensive and time consuming. These equations may be used to estimate the total maximum daily loads for watershed management plans, but for final design, field-monitoring data should be obtained.

Hypothetical-Case Example

A hypothetical urban watershed is presented to illustrate the application of pollutant loading estimation methods as described in this chapter. The total drainage area in this example is approximately 1,200 ha which consists of a mixture of land uses. The areal distribution of each land-use category is shown in Table 7.

Table 7. Land use areal distributions for hypothetical-case example

Land Use	Area (ha)
Low density residential areas	300
High density residential areas	100
School	20
Commercial areas	200
Light industrial areas	100
Parks	280
Streets, total length = 6 km	120
Minor arteries, total length = 2 km	50
Major arteries, total length = 1 km	30
Total	1,200

Area Characteristics

Land use parcel characteristics are addressed in terms of land area with roadway right-of-way (RW) characteristics in terms of width and length. The RWs are measured as assigned widths based upon the following criteria. Streets within a development have an average RW of 20 m, a minor artery has a 25m RW, and a major artery a 30m RW. The profiles for each RW in this case study are shown in Table 8.

Table 8. Roadway right-of-way characteristics for hypothetical-case example

Length (km)	RW (m)	Curb* (m)	Parking* (m)	Landscaped Strip* (m)	Sidewalk* (m)	Traffic Lanes (m)
6	20	2	4	3	3	8
2	25	2	4	3	3	13
1	30	2	4	6	3	15

* Parameters are summed from both sides of the street.

An aggregated analysis was used for the low density (single family houses) and high density residential areas, commercial, school, and light industrial land uses because they exhibited multi-parcel characteristics, such as parking. The lot and aggregated characteristics for residential parcels, commercial, schools, and light industries are presented in Tables 9 and 10, respectively.

Table 9. Lot characteristics for residential, commercial, schools, and industries in hypothetical-case example

Land use	No. of parcels	Each Parcel Area (m^2)	Roof Area (m^2)	Driveway/ Parking (m^2)	Landscaped Area (m^2)
Single family houses	1,200	2,500	500	300	1,700
Apartment buildings	50	20,000	6,000	9,000	5,000
Commercial buildings	20	100,000	45,000	35,000	20,000
Schools*	2	100,000	17,000	23,000	60,000
Light industries	5	200,000	100,000	80,000	20,000

* Areas include athletic fields

Table 10. Aggregate characteristics for each land use for hypothetical-case example

Land Use	Total Area (ha)	Roof Area (ha)	Parking/ Roadway (ha)	Landscaped Area (ha)
Low density residential areas	300.0	24.0	36.0	240.0
High density residential areas	100.0	30.0	45.0	25.0
School	20.0	3.4	4.6	12.0
Commercial areas	200.0	90.0	70.0	40.0
Light industrial areas	100.0	50.0	40.0	10.0
Parks	280.0	2.6	27.4	250.0
Streets, total length = 6 km	120.0	0	84.0	36.0
Minor arteries, total length = 2 km	50.0	0	38.0	12.0
Major arteries, total length = 1 km	30.0	0	21.0	9.0
Total	1,200.0	200.0	366.0	634.0

Litter/Floatable Solids

The empirical equation (Eq. 1) developed by Armitage and Rooseboom (2000) was used to determine annual litter volume (T) in m^3/yr. The estimated litter/floatable solids volume and loading are summarized in Tables 11 and 12, respectively.

Table 11. Calculations of litter/floatable solids volume for hypothetical-case example

Land Use	A_i (ha)	B_i (m^3/ha-yr)	V_i (m^3/ha-yr)	f_{sci}	Litter Volume Eq. (1) (m^3/yr)
Low density residential	300.0	0.01	0.02	1	9
High density residential	100.0	0.02	0.02	1	4
School	20.0	0.02	0.03	1	1
Commercial areas	200.0	1.20	0.03	1	246
Light industrial areas	100.0	0.80	0.03	1	83
Parks	280.0	0.50	0.01	1	143
Total					**486**

Table 12. Summary of litter/floatable solids loading for hypothetical-case example

Land Use	Litter Volume (m^3/yr)	Bulk Density (kg/m^3)	Litter Loading (kg/yr)
Low density residential	9	88.3	795
High density residential	4	88.3	353
School	1	88.3	88
Commercial areas	246	96.4	23,714
Light industrial areas	83	97.8	8,117
Parks	143	88.3	12,627
Total	**486**		**45,694**

The estimated total annual litter and floatable solids loading is about 45,700 kg.

Road Sand

Sand loading estimates, due to winter sand application, were calculated using the method developed by Guo (1999), and the results are summarized in Table 13.

Table 13. Amount of sand discharged to receiving water for hypothetical-case example

Type of roadway	Length (km)	Lane Width (m)	Road Surface Area (m^2)	Sand (1) Application Rate (kg/m^2/yr)	Sand Applied Eq. (3) (kg/yr)	Sand (2) Recovered Eq. (8) (kg/yr)	Sand (3) Transported Eq. (9) (kg/yr)
Street	6	8	48,000	2	96,000	67,200	28,800
Minor artery	2	13	26,000	5	130,000	91,000	39,000
Major artery	1	15	15,000	10	150,000	105,000	45,000
Total							**112,800**

Notes: (1) Local Dept. of Public Works road services inventory records, assumed average values.
(2) Amount of sand recovered by street cleaning operation.
(3) Amount of sand removed by storm runoff and discharged to receiving water.

The amount of road sand discharged into receiving water is estimated to be 112,800 kg/yr.

Street Dust and Dirt

Street Dust and Dirt Accumulation

The Michaelis-Menton equation (Eq.13) was used for estimating the street dust and dirt accumulation between storm events. Results are presented in Table 14.

Table 14. Street dust and dirt accumulation rates and loading for hypothetical case study

Type of roadway	Length (km)	Total Curb Length (curb-m)	Maximum Build Up Limit(1) (g/curb-m)	Estimated Dust and Dirt Accumulation(2) (kg)
Street	6	12,000	250	2,760
Minor arterial	2	4,000	180	660
Major arterial	1	2,000	150	280
Total	9	18,000		3,700

Notes: (1) Selected from published *DDLIM* values, Delleur (2001)
(2) Between storm events loading calculated from Eq. (13): $DDFAC$ = 0.9d and T = 10 d

Street Dust and Dirt Washoff

Street dust and dirt washoff loadings were estimated based on the first-order decay equation (Eq.14) and results are presented in Table 15.

Table 15. Street dust and dirt washoff loadings for hypothetical case study

Type of roadway	Total Curb Length (curb-m)	Estimated Dust and Dirt Accumulation (N_0) Between Storm Events (kg)	Washoff Coefficient (K)	Solids Washoff Loadings to Sewer(1) (kg)
Street	12,000	2,760	0.5	2,530
Minor arterial	4,000	660	0.75	645
Major arterial	2,000	280	1.0	278
Total	18,000			**3,453**

Notes: (1) Loadings per storm calculated from Eq. (14): average rain depth = 5 mm

Each storm carries 3,453 kg solids to the drainage sewer systems. Total solid washoff loadings generated by 20 rainfall (>5 mm) events over a year will be 69,000 kg.

Soil Erosion

The majority of soil erosions are from park open space and landscaped areas. There are no construction activities in the example, otherwise much higher soil erosion would be generated. The calculations of amount of soil loss were based on Equation 15 and results are summarized in Table 16.

Table 16. Soil erosion load for hypothetical-case example

Land use	Landscaped Area		Soil Erosion	
	(ha)	(acre)	ton/yr	kg/yr
Residential, school, commercial, and industrial areas	384	950	25	22,600
Parks	250	620	23	22,300
Total				**44,900**

The total soil erosion from this urban watershed is estimated about 44,900 kg/yr.

Summary of Solids Loading

A summary of total annual solids loadings of each category is indicated in Table 17.

Table 17. Summary of total annual solids loadings for hypothetical-case example

Solid Category	Annual Loadings (kg)
Litter/floatable solids	45,700
Highway/street sands	112,800
Street dust and dirt	69,000
Soil erosion	44,900
Total	**272,400**

A total annual solids loading discharged from the watershed land surface is estimated about 272,400 kg or 272.4 tonnes. However, a highly significant portion of pollution, that in the dissolved solids form is not presented in the estimated values. Solids falling directly onto the surface of a waterway, such as a large lake, during rainfall is not accounted for. Sewer sediment contains very high concentrations of organic (oxygen demanding) pollutants and a significant amount of suspended solids compared to the other categories that are addressed in the Chapter 4.